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Improved Resistivity Interpretation From a New Array Laterolog Tool

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إستنتاجات متطورة في تفسير قياس المقاومة الكهربائية باستخدام الجهاز الجديد لقياس المقاومة المستعرض متعدد أعماق الاختبار

أوليفر فيفري و روجر جريفيثس

أحد الأسئلة الرئيسية في تقييم المكامن هي كيفية الاختيار الأمثل للتقنية التي تستخدم في حساب المقاومة الكهربائية لصخور المكمن. هناك تقنيتان شائعتا الاستخدام – قياس المقاومة التأثيري وقياس المقاومة المستعرض. ولقد راجعنا آخر ما طرأ من تطور على قياس المقاومة المستعرض. أن قياس المقاومة المستعرض متعدد أعماق الاختبار المستخدم حالياً يوفر عدة قياسات مسلطة على خمسة أعماق اختبارية وهي شبيهة بقياس المقاومة التأثيري عديد الأعمال المتحيرة.

كل هذه القياسات أو التسجيلات تستخدم التيارات الموجهة التي ترجع إلى جسم جهاز الرصد بدلاً من رجوعها إلى السطح. وبسبب قرب مكان رجوع التيار توجد مزايا جديرة بالاعتبار منها: تجنب ظاهرة التغير المفاجئ في سمك مسار التيار الكهربائي.

تم تفسير البيانات بواسطة برنامج الحاسب الآلي باستخدام نماذج للمكمن متفاوتة التعقيد للحصول على أحسن قيمة تقريبية للمقاومة الحقيقية لصخور المكمن، ففي موقع البئر تم الحصول على المقاومة الحقيقية باستخدام نموذج سريع أحادي البعد لهذا البرنامج والذي يأخذ في الحسبان تأثير الغمر. وهذه الطريقة بسبب محتواها المعلوماتي المتطور ودقة الرؤية العمودية لها، فهي تعطي قيمة أكثر دقة للمقاومة الحقيقية لصخور المكمن.

أما في المكامن التي تحتوي على طبقات رقيقة السمك، فقد تم عكس أو قلب نموذج ثنائي الأبعاد بحيث يحسب في نفس الوقت التغير في المقاومة الرأسية والمحورية، وقد لوحظ أن هناك تحسناً في حساب المقاومة الحقيقية عندما أخذ في الاعتبار تأثير سمك الطبقات.

إن التحسن الذي طرأ على تصميم الآلة وكذلك معالجة المعلومات نتج عنهما زيادة واضحة في معدل عمل هذه التقنية وأن الأمثلة من التقارير الحديثة تظهر وبجلاء فوائد هذه الآلة الجديدة.

Abstract: *One of the constant formation evaluation questions is that of selecting the optimal technique for determining formation resistivities. Two techniques are in common use, induction and laterolog. We review the latest developments in laterolog logging.*

A recent array laterolog tool, HRLA (High-Resolution Laterolog Array tool), makes several focused measurements, with five depths of investigation, in a way similar to an array induction tool.*

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All measurements use bucking currents returning to the tool rather than to surface. The proximity of the current return has considerable advantages; it eliminates Groningen effects and significantly reduces shoulder effects caused by strong bucking currents returning to the surface, in particular the well-known "squeeze" effect. It also eliminates the need for a bridle, resulting in improved operational efficiency.

The data is interpreted by inversion software using formation models of varying complexities to best approximate the true formation resistivity. At the wellsite, Rt is provided by a fast one-dimensional (1D) inversion that only takes into account invasion effects. Improved information content and vertical resolution results in more accurate 1D Rt determination. In thinly bedded formations a two-dimensional (2D) model is inverted, which simultaneously accounts for both radial and axial resistivity variations. Significant improvements in Rt determination are seen when shoulder-bed influences are taken into account.

The improvements in tool design and in processing have resulted in significant increases in the operating range of the new laterolog. Examples from recent surveys clearly display the benefits of this new tool.

INTRODUCTION

Accurate R_t determination is critical in identifying and estimating reserves. As the industry evolves into the evaluation and production of more complex reservoirs, the importance of accurate resistivity data becomes increasingly apparent. Traditional dual laterolog measurements do not always supply sufficient information to achieve unambiguous interpretations. A review of the limitations of existing techniques and a rethink of both the acquisition and processing of laterolog data was undertaken in order to reduce the uncertainty on R_t and thus improve saturation estimations.

TOOL DESCRIPTION

The objective during tool design was to optimize the measurement information content while minimizing unwanted effects. It is better to minimize unwanted effects at the measurement stage than to compensate for them later.

Borehole and shoulder effects are minimized by the use of laterolog-style focusing, rather than unfocused measurements. Focusing involves injecting current from guard or bucking electrodes to ensure that the current from the central measure electrode flows into the formation rather than along the borehole.

By having all currents return to the tool body rather than surface, voltage reference effects are eliminated and shoulder bed effects reduced. In addition, the surface current return and insulating bridle are no longer needed.

Optimal focusing is achieved with a symmetric tool, which brings the additional benefit that all signals are measured at exactly the same time and logging position. This avoids horns and/or oscillations caused by irregular tool motion and ensures that the measurements are always exactly depth-aligned. Unfortunately the symmetric tool requirement conflicts with the need to achieve a practical tool length while retaining reasonable depth of investigation. This was resolved by using the conductive housings of the tools above and below the laterolog device as part of the array, increasing effective array length while keeping overall toolstring length to a minimum. The resulting tool has been named the High-Resolution Laterolog Array (HRLA) tool[6].

The HRLA tool uses segmented bucking electrodes and multi-frequency operation (ranging from 75 to 270 Hz) to acquire six simultaneous measurements. Two techniques are in common use, hardware and software focusing. The hardware injects the currents in a way that is as close to focused as possible. Hardware focusing alone, however, is subject to physical limitations which, in a dynamic environment such as well logging, result in slight voltage imbalances on the array. Software focusing, whereby mathematical superposition of signals is used to ensure that the focusing conditions are respected, is used to rectify any imperfections.

The result is six focused measurements with varying depths of investigation that are intrinsically resolution-matched and depth-aligned. The shallowest mode, RLA0, is mostly sensitive to the borehole and is used to estimate the mud resistivity. The apparent resistivities RLA1 through RLA5 are all sensitive to the formation, becoming progressively deeper in investigation. The current patterns of these five modes, in a homogeneous 1-ohm-m. formation, are shown in figure 1.

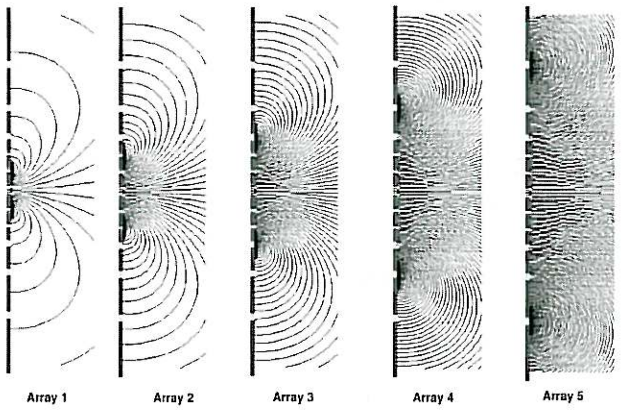

Fig. 1. Current distributions for HRLA resistivities RLA1 to RLA5 in homogeneous 1 ohm-m. formation.

Data from field tests of an experimental version of the HRLA tool was used to optimize the differentiation of the measurements by adjusting the array spacings. Figure 2 shows the radial response of the optimized HRLA tool compared to the HLLD and HLLS measurements from the High Resolution Azimuthal Laterolog Sonde (HALS) tool[5].

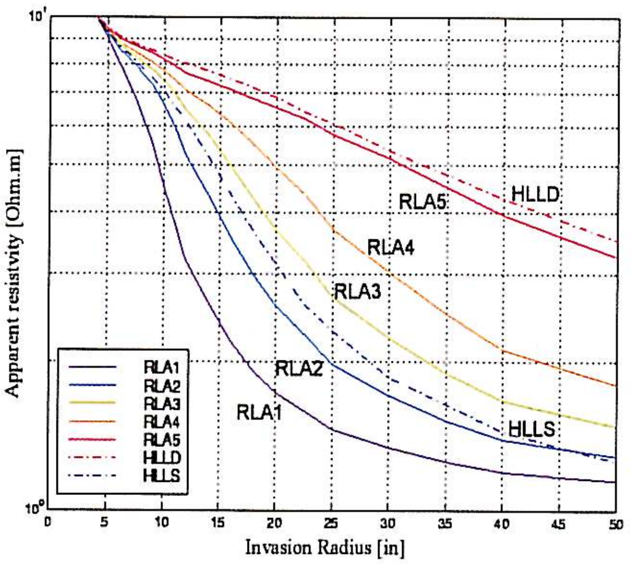

Fig. 2. Radial response of the HRLA resistivities compared to HLLD and HLLS from the HALS tool: Borehole-corrected apparent resistivities in a thick bed as a function of the invasion radius. R_t = 10 ohm-m, R_{xo} = 1 ohm-m, d_h = 8 in., and R_m = 0.1 ohm-m.

The borehole corrected resistivity readings are computed in an infinitely thick bed as a function of the invasion radius. The apparent resistivities, RLA1 through RLA5, from the HRLA tool, HLLD and HLLS from the HALS tool, all read true resistivity when the bed is uninvaded. When the invasion diameter increases the channels start dropping towards the R_{xo} value at a rate depending on their depth of investigation. The array laterolog tool response is very similar in character to that of the HALS tool, with the RLA5 measurement showing comparable response to that of the HLLD. The spacing of the array has been designed to optimize the information content of the data with respect to the invasion profile. The HRLA tool, with three additional curves, delivers greater detail about the invasion profile. This is especially important in thin beds, where "deeper" measurements tend to loose some depth of investigation and hence differentiation due to anti-squeeze effects.

FIELD EXAMPLES

Improvements in instrumentation have permitted electrode spacing reductions in recent sensors such as the ARI Azimuthal Resistivity Imager and HALS tools. This yields an improvement in vertical resolution which has been continued with the HRLA tool as is evident in the field log in figure 3 that compares the HRLA

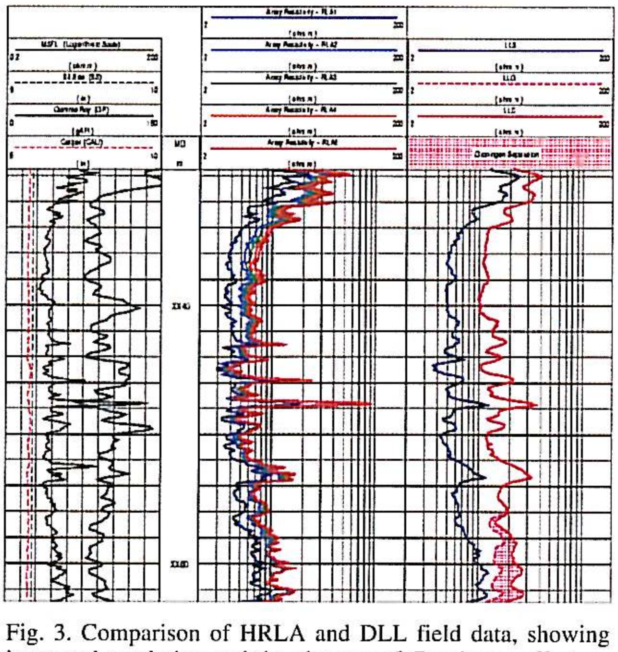

Fig. 3. Comparison of HRLA and DLL field data, showing improved resolution and the absence of Groningen effect on the HRLA response. Microresistivity is presented in the left track to confirm the high-resolution HRLA data.

response to the DLL response. The R_{xo} measurement is presented in the left track to show that the response of the array laterolog is verified by other high-resolution measurements. This well penetrates a sequence of thin beds overlain by a highly resistive anhydrite layer. This layer interferes with the deep mode current return of the dual laterolog resulting in Groningen separation as shown by the shading in the third track. The LLD reads too high over the entire interval. In contrast, the HRLA resistivities are not subject to Groningen effects. Toward the top of the interval invasion is indicated by the coherent spread of the array resistivities while the DLL data can not be used without further corrections[8].

Figure 4 shows a comparison of HRLA and DLL logs. The LLd and LLs separate nicely, which could be taken as an indication of hydrocarbon. This is in fact due to Groningen effect, and all the HRLA curves are stacked together indicating clearly a water zone.

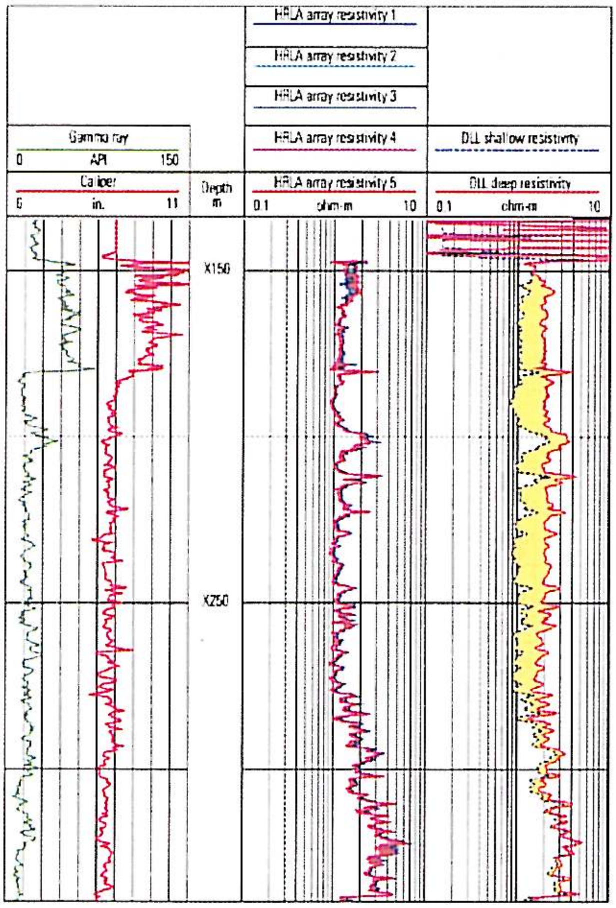

Fig. 4. Groningen effect visible on the dual laterolog is absent from the HRLA response shown in the middle track.

Figure 5 shows the wellsite-computed 1D R_t and d_i from both the HRLA and HALS tools. In resistive beds where the HALS resistivities are out of sequence owing to shoulder bed effect, the diameter of invasion is forced to bit size (i.e., no formation invasion). Over the same interval the R_t is equal to HLLD, as the input data is inconsistent with the 1D formation model. The additional information available from the array resistivities allows a realistic estimation of the invasion diameter, which in turn allows invasion corrections to be applied to find a more accurate R_t. The R_t computed in real-time at the well site (before shoulder-bed correction) from the consistent HRLA data will be more accurate than R_t computed from the HALS. For the peak around xx00 ft. the R_t found is about 45% higher: over the entire interval shown an increase in the reserves estimate of 16% was found compared to the HALS data. Note that shoulder corrections can be applied in post-processing to the HALS data (1D+1D), in which case a better R_t results, close to that computed from the HRLA data

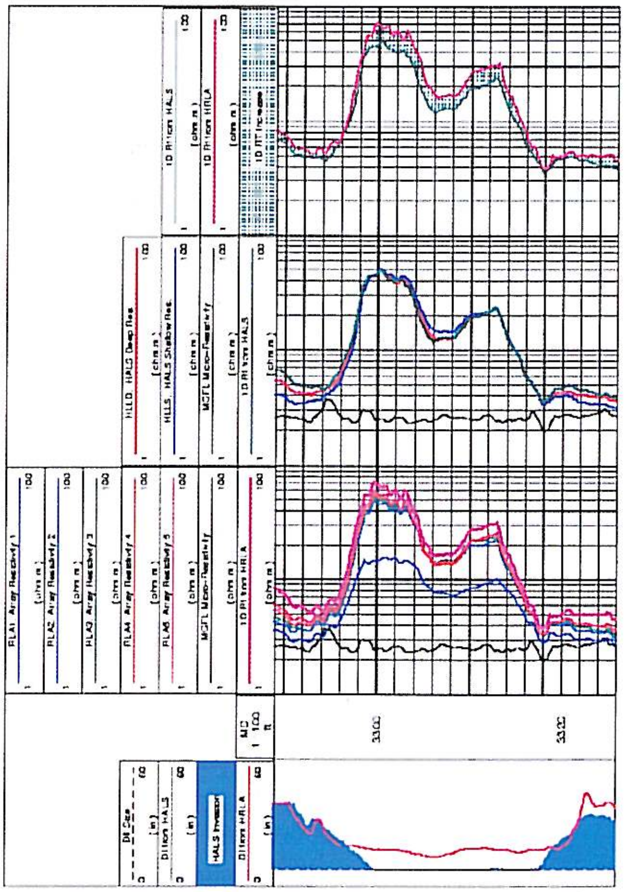

Fig. 5. Comparison of HRLA and HALS data, showing reduced shoulder bed effect and improved characterization of invasion which lead to better 1D inverted R_t.

2D INVERSION

Traditional resistivity determination by laterolog[7] involves a "deep" and "shallow" measurement in conjunction with a micro-resistivity pad device. The micro-resistivity device measures the resistivity of the near-wellbore zone invaded with drilling fluid filtrate. The separation of these three resistivities is taken as an indication of an invasion profile when the invading and connate fluids have different resistivities.

This one-dimensional (1D) approach, graphically represented in figure 6, only considers the radial effect of formation invasion. It does not address the fact that the reading in a bed may be influenced by the surrounding beds. This 1D assumption may be valid in thick homogeneous beds with relatively small resistivity contrast to the surrounding beds, but in thin invaded beds the 1D assumption can lead to significant errors in resistivity determination.

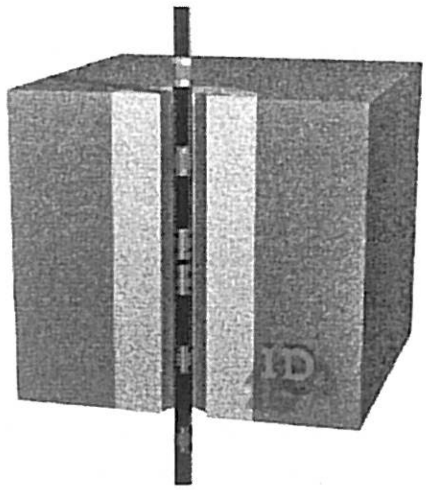

Fig. 6. Oversimplified formation model. The application of a 1D model that ignores 2D borehole and shoulder bed effects can lead to inaccuracies in formation resistivity estimation.

It has been recognized that formation resistivity estimation can be improved by use of inversion techniques that take into account the true 2D or 3D formation structure[2,3,4,5,6]. The first step, then, is to define a formation model that more accurately reflects the subsurface. Figure 7 shows the two-dimensional, piston-invasion formation model proposed to represent the subsurface. An obvious extension of this is the construction of models that include dipping layers (2.5D) and azimuthal resistivity variation (3D).

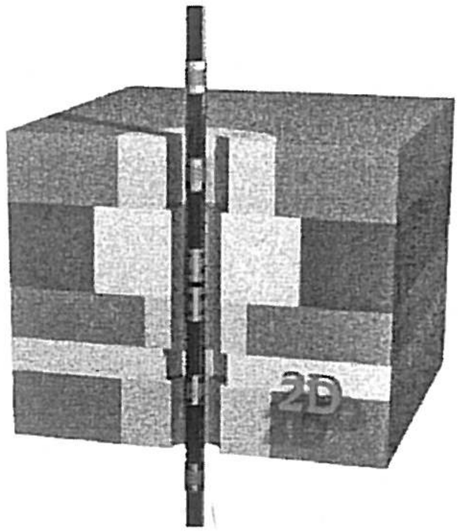

Fig. 7. The 2D-formation model takes into account the borehole, shoulder bed and invasion effects simultaneously.

In order to solve for these more complex formation models it is beneficial to increase the measurement information content by use of multiple-spacing electrode arrays similar in concept to the multiple-spacing induction arrays. A critical aspect of this approach is to ensure that the differentiation between the array measurements is larger than the uncertainties within each measurement.

The processing chain is outlined in figure 8. The first step is the definition of the formation layering. This is normally achieved by inflection point segmentation of the resistivity log. Initial

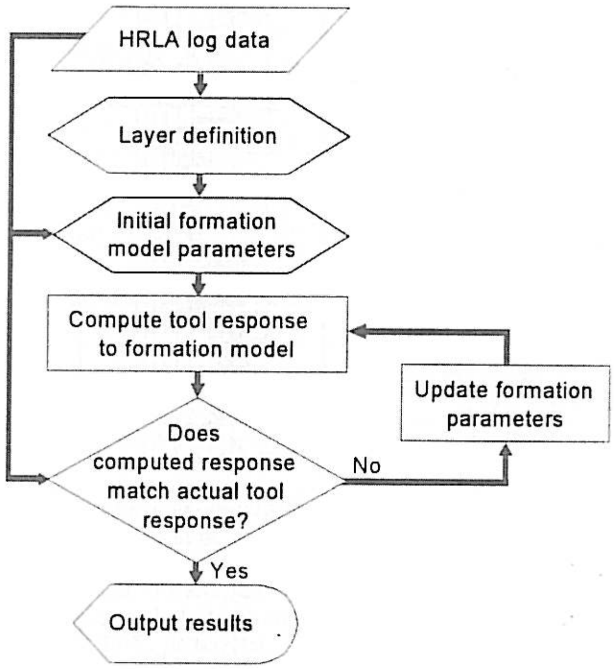

Fig. 8. 2D inversion processing chain.

formation parameters (R_t, R_{xo} and d_i) are then derived from the input resistivity data. A 2D Finite Element forward model is then used to compute the tool response to this initial formation model. The computed response is compared to the actual measurements and adjustments made to the formation parameters. This process of tool response modeling and formation model refining is iterated until a good match between the computed and actual tool response is found. By modeling the effects of the borehole, invasion and shoulder beds in two dimensions, their interdependent effects can be accounted for by the inversion process. Thus more accurate formation resistivity parameters, R_t, R_{xo} and d_i are found

Substantial improvements in estimated reserves have been seen during field testing of the tool and inversion. The field example shown in figure 9 indicates a significant increase in the calculated R_t in the reservoir zones. The stability of the inversion is remarkable considering the high activity of the logs. Note the ability to handle alternating normal and reverse invasion profiles and the good match between inverted R_{xo} and the R_{xo} measured by the Micro-Cylindrically Focused Log (MCFL) tool except where the MCFL data is affected by borehole rugosity.

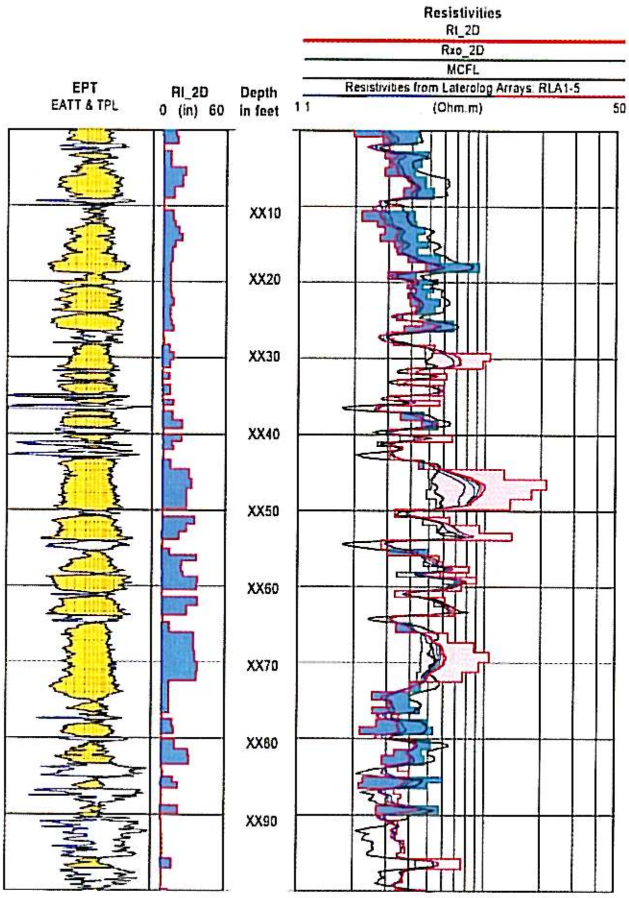

Fig. 9. 2D Inversion on HRLA field data showing significant R_t increases in the reservoir zones. Note the consistency between the R_{xo} extracted by the inversion from the HRLA data alone and the R_{xo} measurement, MCFL. Below XX80 ft the low R_{xo} measurements are due to hole rugosity and hence do not match the HRLA derived R_{xo}. Note also the stability of the inversion in handling both normal and reverse invasion profiles.

CONCLUSION

A new solution methodology, which combines an improved formation model with a mathematical inversion technique capable of extracting the enhanced information available from a new electrode array resistivity tool, provides better formation resistivity values.

The advantages of the HRLA tool, which minimizes unwanted effects, have been demonstrated both on synthetic benchmarks and several field data sets. Important advantages include the absence of voltage reference effects and reduced shoulder effect. These tests have shown high vertical resolution and improved invasion discrimination in thinly bedded formations, leading to an improved R_t estimate after inversion processing.

At the wellsite, operational safety and efficiency is improved by the elimination of the bridle and surface current return system. The real-time 1D processing benefits from the increased information content, reduced shoulder effects and the absence of Groningen and drill-pipe effects.

Application of robust inversion processing, based on a 2D formation model, to the array resistivity data yields improved formation parameter estimates. In many cases calculations of hydrocarbon saturations are considerably increased, particularly in thinly bedded formations.

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